Review of internet-of-things enabled geotechnical monitoring hardware for tailings storage facilities.

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Monitoring has been a part of tailings storage facilities (TSF) for decades. Instruments themselves have proven designs that have become the backbone of monitoring but in recent years, advances in batteries, radio technologies, microprocessors and telecommunications have enabled the Internet-of-things to become an important part of TSF monitoring. The introduction or several new protocols such as LoRa, ZigBee or mesh-based TCP have greatly increased the available connectivity of instruments in TSF. By comparing the technologies offered by several manufacturers, we will show that several parameters have to be optimized concurrently to design robust internet of things (IoT) systems. Typically, a balance has to be found between radio functionalities such as bandwidth and response time, range, power requirements and compatibility with a broad range of instruments. Typical radio ranges are between 1 and 15 km and can be expanded with mesh networking in some cases. Low power requirements are required in many situations because instruments are remote, isolated and the only available power source is sunshine. Compatibility has to be met with a wide range of instruments signal types such as vibrating wire, thermistors, RS-485, SDi-12, 4-20 mA, time-domain reflectometry and many more.

IoT best practices such as interconnectivity and the possibility to bring disparate technologies are applications into a single framework. Other IoT practices such as self-configuration and intelligent monitoring will be discussed in various contexts. Real-time data puts very different constraints on the hardware when performing background readings that are updated once per month compared to smart sensors that are triggered by external events such as seismic monitors. These new IoT practices also lay the groundwork for future developments such as the use of machine learning and AI for more proactive monitoring of assets.

INTRODUCTION

Unfortunate events in recent years have increased the general awareness of the issues posed by tailings and tailings dams. Several major failures, notably in Brazil (Brumhandino), the United States (Florida) and in the Philippines (Benguet province), have shown that deploying remote monitoring techniques could greatly improve long-term safety by providing engineers and mining companies the data they need to make informed decisions. Industry 4.0 practices such the Internet of things (IoT) paradigm have started to make their way into the monitoring of tailings storage facilities (TSF). The IoT is a growing field in which devices are connected to the internet or a local network automatically and with a unique identifier. In many industries, the IoT sees success as a way to collect data from monitoring points, instruments, and the status of machines and data logging systems. We will give an overview of IoT as applied to TSF monitoring. This review will cover the benefits of IoT systems, how the different hardware and software layers are interconnected. It will also compare the features of several manufacturers of IoT hardware for TSF and how to take advantage of the most appropriate products. This will be followed by a short discussion of the functions that TSF monitoring software should have to take full advantage of IoT systems.

IoT Characteristics

Monitoring is an integral part of the culture surrounding TSF. Piezometers, water sampling, surveying and more have been used consistently to ensure the durability and safety of tailings for decades. For some older facilities, instruments such as piezometers have been in the ground for decades and are still in use. Bringing an IoT framework to this field is an evolution prompted by the decreasing costs and increasing power of microprocessors and radio communications (RF) modules. By attaching specific devices to the instruments, an already-existing network of instruments can be converted to an IoT system. In the context of TSF and environmental monitoring at large, an IoT system is a system that monitors and controls sensors over a wide area, whose data are connected remotely and centralized in a server. IoT systems should have several of the following characteristics to varying degrees:

Dynamic and self-adapting
The IoT system should be able to integrate new instruments and deploy redundancies without minimal user intervention. A typical example of this is to take advantage of a centralized server to coordinates the readings of remote instruments of a single site after a seismic event is reported.

Self-configuring
Deploying an instrument should be as simple as turning it on after installation.

Interoperability
In tailings and environmental monitoring, there are different manufacturers of sensors, data loggers and instruments. There are very standards. A well-designed IoT system should be able to accommodate many types of instruments and allow the instruments to interact as needed.

Unique identity
Each instrument can and should have a unique identity built-in into the system. This acts as a stronger redundancy to manually tracking instrument locations, installation parameters, serial numbers and calibration factors.

Integration into larger data networks
An IoT system should be able to allow analysis and comparison of data from many different sources and sites. For instance, working on weather stations, ground-based radar, InSAR and in-ground instruments can lead to insights that were previous unattainable.

Context awareness
In the case of tailings, the context varies very little over time once the instrument is in the ground. While this is a common characteristic of IoT systems, it doesn't apply to well. An example for this is tracking systems on fleet vehicles or safety trackers on workers. These devices should be able to respond accordingly to the location of the worker but also to the locations of surrounding heavy machines.

Intelligent decision-making
Tailings monitoring systems should be able to lead to more intelligent decision-making.

IOT ARCHITECTURE

Table 1 summarizes the structure of an IoT project as used in tailings storage facilities. The instrument layer is the instrument itself. An un-depth analysis of instrument types and technologies is beyond the scope of this review insofar as the instruments are largely decoupled from the IoT hardware. Instruments often installed in the ground and as such cannot have any type of telemetry built-in to them due to the physical constraints of the soil blocking any kind of RF communications. The node layer usually comprises a data logger, an RF module and a power source. The edge device connects the node together, to a local network or to the internet. The management layer is a software layer that assists in the data and inventory management of the instruments and nodes. The application layer is where all data is aggregated and used for monitoring, modeling and more. While in most systems the layers are well-defined, the exact limit separating them can be blurred. For instance, individual nodes can contain an edge device or contain some level of management tools allowing for data quality control before outputting the data on the network.

Table 1 Table detailing examples of items part of each of the 5 layers of an IoT system for TSF

1. Instrument	***2. Node***	***3. Edge Device***	***4. Management***	***5. Application***
Piezometers	Data logger	Cellular	Instrument inventory	Graphing
Total station	Radio module	Satellite	Data archiving	Automated reports
LIDAR		Gateway	Security	Data analysis
Inclinometers		Distributed gateways	Traceability	Specialized tools

INSTRUMENTS AND NODES LAYERS

Nodes are network-enabled devices can transmit readings over RF, collect data from instruments and in most cases locally store the data. They may use a broad variety of standards and protocols to establish communications such as Zigbee, LoRa, Pakbus, and proprietary versions or implementations of each, as well as generic-purpose products such as WiFi and LTE. Using this intermediate step i is usually necessary for TFFs specifically: attaching an internet connection point to to each instrument is not possible in TSFs due to the high costs wiring and managing power.

Zigbee, LoRa, Pakbus and other associated RF protocols can be sorted in two broad families: Star and mesh networks. Star topology relies on having a transmitter at each instrument/location that transfers directly to an edge device, typically called a gateway (Figure 1 (a)). This link can be unidirectional (the instrument transmits its data on a schedule or when certain conditions are met) or bi-directional, in which polling and other operations can be initiated over the link. Star topology has several advantages over mesh networks: it is simple to use, simple to understand and to manage. While very simple, star networks have a few constraints that have to be carefully considered. There is no way to reroute the data around obstacles should the topology of a site change. It is also not typically possible to extend the range by adding repeaters.

However, the most commonly used technology for star networks, LoRa, has a range of up to 15 km, easily covering even the largest TSF.

In mesh networks (Figure 2 (b)), nodes can communicate with each other and transmit relay data between them and all the way up to the gateway or edge device. These networks are often self-healing: if the radio link between two specific nodes is broken, data can be automatically rerouted. The radio technology behind this is more complex than what is required for star networks, but mesh networks tend to more resilient and have fewer points of failures than star networks.

Several manufacturers offer products that work under this principle to enable IoT practices in0 A comparison of the specifics of each technology can be found in table 2. This list is not exhaustive and is only meant to be representative of the author's professional experience working in North America.

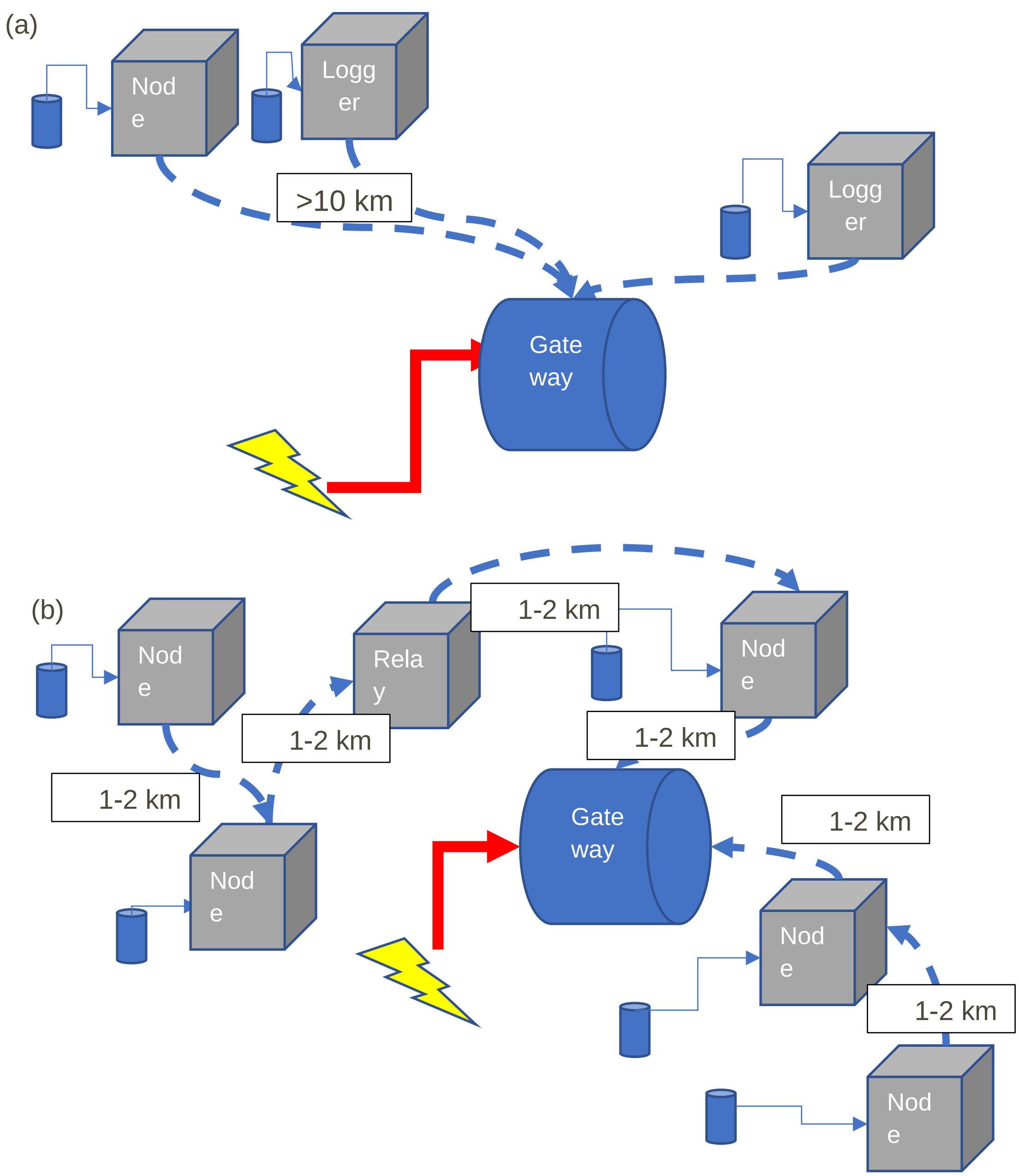

Figure 1 (a) Schematics of a star network. (b) Schematics of a mesh network.

Table 2 Point-by-point comparison of a selection of IoT dataloggers commonly found in TSF applications.

	Protocol	*Net. type*	*Self-healing*	*Nb. of hops*	*Range outdoor*	*Range indoor*	*Edge device*	*Instr. Per node*	*Batt. Life*
Ackcio	Mesh-LoRa	Mesh	Yes	>10	10 km	1 km	Prop. Gateway	1-8	10 yr.
Geokon	Mesh	Mesh	Yes	4	6 km	300 m	Prop. Gateway	1-8	1 yr.
Campbell Scientific	Pakbus	Cust.	N/A	>10*	40 km	1 km	Any	Many	1 yr.
RST	Prop.	Star	N/A	N/A	14 km	1 km	Prop. Gateway	1-40	5 yr.
Senceive	Prop. Mesh	Mesh	Yes	>25	500 m	200 m	Prop. Gateway	1-4	10 yr.
Sensemetrics	Prop.mesh	Mesh	Yes	?	12 km	1 km	Each node	Many	Solar
Worldsensing	LoRa	Star	Yes*	N/A	15 km	1 km	Prop. Gateway	1-5	10 yr.

**Limited by end-user programming.*

Delving in specifics of each technology is beyond the scope of this paper but a few key differences are highlighted in this section. All products are compatible with vibrating wire instruments such as piezometers. All but Geokon's Geonet are compabitle with analog output instrument such as barometers or temperature sensors. Digital instrument (e.g., addressable thermistor strings, addressable in-place inclinometers, digital weather stations, etc synchronizes.) are on a case-by-case for each instrument for every manufacturer as the drivers have to be programmed on request by the manufacturers.

Ackcio

Ackcio products have compatibility with vibrating wire instruments and a large number of digital instruments such as digital in-place inclinometers from leading manufacturers. The nodes deploy a self-healing mesh network that can cover very large areas. The nodes have a large on-board memory. The gateway the network and offers an ethernet connection, a wifi connection and a cellular network connection.

Geokon

Gekon's Geonet product deploys a mesh network with a limited range and a limited number of hops compared to other options such as Ackcio and Senceive. They are compatible with vibrating wire instruments Geokon digital instruments. The gateway synchronizes the network and can be configured to contain a cellular modem with either an LTE-M or 3G connection.

Campbell Scientific

Campbell scientific products have been used for decades and are robust devices that are very flexible in their programming. The manufacturer is however somewhat lagging behind as far as newer IoT practices go. However, the PakBus radio technology (Campbell's proprietary protocol) is flexible if not user friendly.

The loggers are completely customizable and programmable, allowing for compatibility with all types of instruments available on the market. While the IoT functionality is not fully realized, these products are often the most cost-effective approach when a large number of instruments is to be connected to a single location. Most other systems discussed here can only accommodate a few instruments each whereas Campbell Scientific loggers can be easily expanded to read hundreds of instruments.

RST

RST's R-Star line of products works on a purely star network architecture with a long-range using a proprietary protocol. RST offers their own line of loggers that are compatible with all analog and vibrating wire instrument as well as their own digital instrument. There is also a module that allows connection of already-existing Campbell Scientific loggers to an RST network. The gateway offers connection to the internet.

Senceive

Senceive's line of products offers the most robust mesh network in terms of range, number of hops, number of nodes and stability of the products discussed in this review. They offer compatibility with vibrating wire and analog instruments. The nodes have a long battery life, but they are the only product that can't be used in standalone (i.e.non-networked data logger) or have an on-board back up memory. If the gateway is out of commission for whatever reason, no data will be acquired until the network is restored.

Sensemetrics

Sensemetrics employ a unique approach. The nodes (THREADS) are all gateways with an ethernet connection that can also communicate with each other with a mesh network architecture. Each THREAD is compatible with most digital instruments but requires external accessories of other manufacturer's data loggers (such as Geokon's Geonet or LC-2) to read vibrating wire instruments. It is also the only system discussed in this review that has a proprietary cloud platform for configuration and management of the loggers and instruments. The battery life of individual THREADs is low, and they typically require a solar panel for continuous operations.

Worldsensing

Worldsensing products (Loadsensing) work on a purely star network (LoRa) with a very long radio range. The nodes require very little power and have a battery life of years or more. Nodes are compatible with vibrating wire instruments, analog instruments and a select number of digital instruments.

EDGE DEVICES LAYER

Edge devices layer comprises the device that connect the local IoT network to the internet. In other fields, instruments themselves have their own connectivity, but the lack of local networks and power supplies on TSF makes impossible direct connection of each instrument. Many products, such as RST's RSTAR, Senceive, Worldsensing, Ackcio and others use a gateway that acts both as the collection point for the local IoT network and as a connection point for the internet. Some gateways offer different means of connection, typically to a local network over an ethernet cable or to a cellular or satellite mode.

Other products, such as Sensemetrics' THREADS distribute the edge connectivity with each Thread being a data logger, radio transmitter and internet connection point. This gives the most flexibility and redundancy but increases operation costs. It's usually preferable to have fewer edge devices that aggregate data from several nodes due to the extra cost and power requirements incurred by cellular modems, built-in or external.

In a few cases, the instruments themselves connect to the internet or a local server but this is unusual in the tailings monitoring. Cellular modems are commonly built-in into strong motion sensors or seismographs. The typically large amount of data generated by this type of instrument makes it impractical to transmit measurements over local radio links.

MANAGEMENT LAYER

The management layer is both a benefit and a core component of an IoT system. In TSF and geotechnical monitoring the standard is to know exactly why an instrument should be at a given location, what is expected to be learned from it and how to handle its data. Even with these widespread precautions, it is not rare for practitioners to lose track of the instrument inventory, of historical data or to ignore data. Large mining companies are showing interest to fully automate their monitoring systems in tailings across the world. This compounds the aforementioned data and instrument management issues as tens or hundreds of sites will be managed concurrently in large companies. In addition to the large number of instruments scattered around the globe, the engineering teams are often located remotely and can oversee several mines, making good management practices that much more important. This section will give an overview of recommended practices and review of existing features in several software to better manage data, users and instruments. Much like for hardware, there are many different platforms available out there. The commercially available platforms discussed here are not an endorsement and reflect the products encountered by the author in various TSF monitoring projects.

Data logger management

Some platforms, such as Vista Data Vision and Multi-Logger Canary are not typically fully integrated with the hardware, they pull data from. It makes them more versatile as they are designed to be compatible with text-based data files and other data sources but in return, they typically can't interact with the hardware. This interaction can be beneficial by allowing for manually triggered measurements health check of the dataloggers. Newer platforms such as Sensemetrics allow not only to have access to all instruments information in a centralized database, but also to have direct access to health and status of the instruments and loggers, making proactive maintenance much easier and cost-effective. This is done at the expense of flexibility and interoperability.

Other features are found in most platforms that facilitate the management of large instrument numbers. Alarms can be set on out of bounds signals, on battery voltage or on logger temperature. Every available platform offers this type of functionality, and they make overseeing large number of instruments much more manageable. A properly designed IoT systems has tools to uniquely identify instruments, measurement point, calibration factors, maintenance operations and documentation. Such a centralized system becomes critical as IoT systems grow larger and more complex.

Data tracking and archiving

A common pitfall of large-scale monitoring systems is the traceability of data over years and decades. Modern techniques of integration in databases helps prevent this. Though it is now commonly achieved in an "Io" framework, this has been an industry 4.0 practice for decades in manufacturing and retail, with dedicated databases for instruments, often included in ERP (enterprise resource planning) packages due to how data from a factory relates in real-time to its financials. TSF need "slower" monitoring and only recently have we started seeing dedicated database systems for this industry.

Mines that have been in operation for decades or that have ambitious monitoring systems can generate more data than is easily manageable by a human team. Progressively moving away from manual tallying, we have seen dataloggers dramatically increase the amount of data collected per instrument without the proper data management tools having been put in place. The author has seen a large gold mine use 500 Mb Excel files to plot their TSF data. This method is unreliable and is prone to human error. This mine has been in operation for only a few years and this situation could have been planned for from the beginning. Having everything catalogued in a searchable database ensures long-term traceability of all data.

Data distribution and access rights

In any given organization, several teams might want to access the data: production, environment, health and safety, and engineering. Every IoT platform should have some form of data sequestering, user management and access rights. Though the details may vary, every platform, offers this in some way or another with varying degrees of autonomy given to individuals to manage their own projects and access rights.

APPLICATION

The application ties together the hardware into an actual IoT system. The software should have two main components: hardware control and data management. We have already touched upon some of the hardware control requirements: status updates on the instruments, inventory management, etc. In addition to the aforementioned management features, many features for the front-end should be more commonplace. Commonly found functions such as graphing of historical data or report generation have been introduced over a decade ago by the software companies such as Vista Data Vision or Geoexplorer. However, with the increasing number of connected instruments and the wider variety of instrument technologies used, more and more features are now recommended to be present. For instance, total stations, ground-based radar and INSAR have now found their place in tailings monitoring. While they are contactless and are not IoT *per se*, their data is complementary to that of in-ground IoT instruments that it should be treated concurrently with these instruments.

Some commonly used instruments require specific tools for plotting and interpreting data. In-place inclinometers and manual inclinometer probes have notoriously tricky data to analyze that can’t be displayed accurately on regular time graphs. Distributed monitoring such as ground-based radar and total stations also require specialized tools for plotting. The application layer chosen for an IoT system should include the necessary tools for the instruments of a given TSF monitoring system.

Because industry 4.0 offer a more direct integration of geotechnical data, functions often found in SCADAs and other industrial system are now recommended to be added to TSF monitoring system. Real-time alarms, an alarm logging tool, user management are all now becoming standard in this industry.

The application layer encompasses emerging technologies such as machine learning and artificial intelligence. Access to large data sets is necessary to train most machine learning and AI algorithms and the IoT will finally generate the amount of data needed. We will likely see an increase in the application of these methods to TSF in the next five years.

CONCLUSION

The IoT and industry 4.0 are major trends in TSF that are going to change the face of the industry. By understanding the properties of the IoT and the different layers of it, modern and efficient IoT systems can be designed and deployed in TSF. They open the door to automated monitoring of the TSF themselves, but also of the instruments, data loggers and data quality. A growing number of providers offer hardware that can read instruments such as piezometers and make their data available online for management and analysis. Each have specific limitations that need to be taken into account when designing a monitoring system: instrument compatibility, radio range, radio network type, battery life, etc. The hardware directly ties into the various layers of an IoT system sometimes merging several layers into one or leaving them completely independent from each other. As a general rule, the more integrated the layers are, the more the key benefits of an IoT system (Dynamic and self-adapting, Self-configuring, Interoperability, Unique identity Integration into larger data networks, Context awareness and Intelligent decision-making) are developed but at the expense of flexibility and programmability.